Field Alignment of Quadrupole Magnets for the LHC Interaction Regions

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Abstract - High-gradient superconducting quadrupole magnets are being developed by the US LHC Accelerator Project for the Interaction Regions of the Large Hadron Collider. Determination of the magnetic axis for alignment of these magnets will be performed using a single stretched wire system. These measurements will be done both at room and cryogenic temperatures with very long wire lengths, up to 20m. This paper reports on the stretched wire alignment methodology to be employed and the results of recent room-temperature measurements on a 2 m model magnet with long wire lengths.

I. Introduction

The low-β insertion quadrupoles currently under development at FNAL and KEK will have their alignment parameters measured after being installed in cryostats at FNAL. As these magnets provide the final focus before collision for the LHC beam, their alignment must be accurately determined. Such alignment measurements are required at both room and cryogenic temperatures because only the FNAL magnets will undergo testing at cryogenic temperatures; the remaining magnets will rely on warm alignment measurements and measurement of the correlation between warm and cold alignment parameters. Furthermore, although the length of the MQX magnet assemblies range from 5.5 to 6.5 m, the Q2 has two such magnets and a corrector package housed within a single cryostat approximately 15 m in length. When mounted on a test stand, with cryogenic end cans, alignment measurements must be performed within a beam tube of length ~20 m.

The alignment device chosen for these measurements is a Single Stretched Wire (SSW) system of the type used at DESY for the HERA quadrupoles [1] and for the Main Injector quadrupoles at FNAL [2]. The goals for the system are measurement in the transverse plane of the average quadrupole axis (vertical and horizontal) to 50 μm and roll to 100 μrad (including transfer to magnet fiducials) under the measurement conditions cited above. In addition, in order to place the Q2A/Q2B device so as to minimize the effects of relative misalignments of the separate elements (which cannot be adjusted after installation in the cryostat), the true axes of the individual Q2A/Q2B magnets must also be determined (rather than just their average centers). This paper outlines the system and techniques that will be used to achieve these measurement requirements and presents the results of recent tests of the methods involved.

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II. General Measurement Approach

A single wire is stretched between two sets of precision motion stages as shown schematically in Fig. 1. The return wire of the loop lies fixed on the bottom of the beam pipe or outside the magnet.

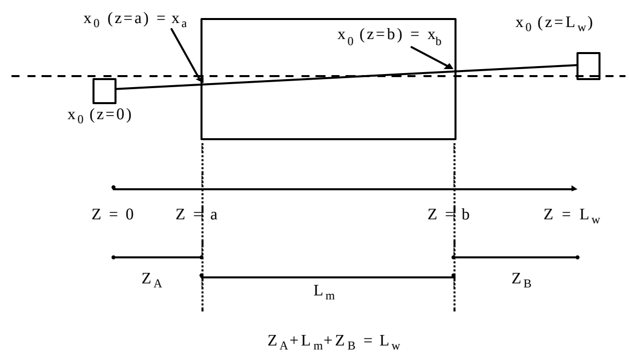

Fig.1. Coordinate definitions for SSW and magnet system

The vector potential at the center of the quadrupole field of gradient g can be expressed as

$$A_z = \Re\left[\sum_{n=1}^{\infty} gR \, \frac{\left(b_n + i a_n\right)}{nR^{\,n-1}} \left[\left(x - x_0\right) + i\left(y - y_0\right)\right]^n \right] , \quad (1)$$

where n, b_n, a_n are the multipole order, and normal and skew coefficients, R is the reference radius, x,y are the horizontal and vertical positions in the wire's frame of reference, and x_0, y_0 are the offsets in the magnet coordinate frame. The change in flux as the wire is moved from point (x_1,y_1) to point (x_2,y_2),

$$\Phi = L_m\left[A_z(x_2, y_2) - A_z(x_1, y_1)\right] , \quad (2)$$

depends only on the start and stop points of the wire and not on its path. When the wire is on average at quadrupole center, positive and negative wire motions result in the same flux change. The wire endpoints on the stages can then be related to fiducials on the magnet cryostat to transfer this average center. Advantages of this type of measurement include its integral nature, highly accurate control of position, and simple geometry. Challenges arise when signal strength is low or when long wire lengths, requiring precise corrections for sag, are employed.

III. SSW System Details

A. Features

1) Wire Motion: The SSW motion system is comprised of two sets of x-y stage units mounted on a z-bracket attached to a flat aluminum base plate. A picture of one stage unit is shown in Fig. 2. The stages have tolerances for straightness and flatness of motion of 1.5 μm per 25 mm. Linear encoders with accuracy of 1 micron record the actual distance of stage travel. The orthogonality error of the x-y assembly is less than 25 μrad. The base plate has its surface parallel to direction of x-stage travel and its edges perpendicular to x-stage travel so that these surfaces can be used for roll and yaw alignment of the units respectively.

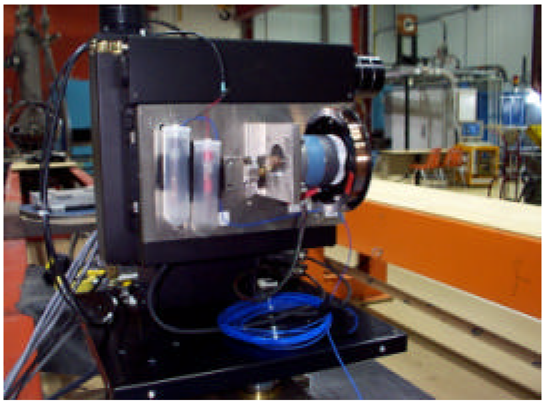

Fig.2. SSW stage unit

The stage units have length, width and height dimensions of roughly 40 cm and weigh ~ 35 kg. Small size and weight allow the units to be easily transported and swapped end-for-end. The stages are fitted with a stepping motor at one end, used to remotely tension the wire, and a tension gauge at the other.

2) Wire: BeCu wire is typically used for its high strength to weight ratio (low sag) and low magnetic susceptibility. More recently, measurements have been performed with Mg wire (AZ61a), which has 35-60% better strength to weight ratio but is somewhat harder to handle.

3) Wire Guides: The wire is constrained on a wire guide comprised of two ceramic ball bearings of diameter 1.2 mm as shown in Fig. 3. Such a wire guide allows precise constraint of the wire for a range of wire diameters, is resistant to wear, and electrically isolates the wire.

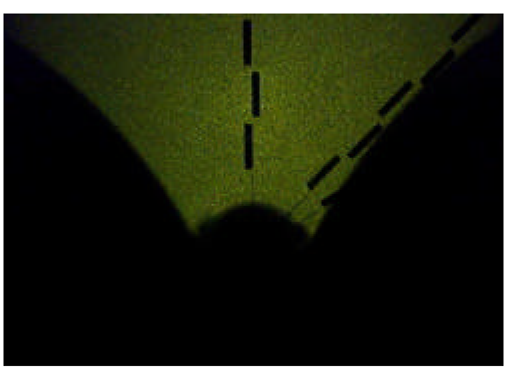

Fig.3. 100 μm wire on 1.2 mm ball bearing wire guide.

4) Flux Measurement: A Metrolab digital integrator (PDI5035) is used to measure the change in flux with wire motion. The electrical connections from the SSW to the integrator are made within a double flask assembly which provides thermal isolation. This minimizes changes in thermovoltages which cause non-linear drift in the integrator (linear drift is easily removed).

5) Wire Position Transfer: The stage units have nests for receiving laser tracker retro-reflector targets. Wire position with respect to these retro-reflectors is determined using a "contour-projector" – a device which accurately measures distances of silhouetted objects illuminated by a mono-chromatic light source (see e.g. Fig. 3). Wire position to stage retro-reflector center position is measured with accuracy 10 μm. The laser tracker used for transferring to magnet fiducials has measurement accuracy of 25-50 μm.

6) Stage Unit Supports: The stage units contact the test stand support on three spherical feet: allowing easy adjustment of yaw, pitch, and roll angles. Stage travel in x and y is 150mm, thereby facilitating translation adjustments.

B. Measurements

1) DC Measurements: For large signal strengths, e.g. $\int g\, dl > 5T$, determination of alignment parameters can be made at DC magnet currents by measuring flux change during wire motion. For example, for a measurement in x with magnet roll ~0 (i.e. where a_2 ~ 0), the vector potential reduces to

$$A_z = \frac{b_2}{2}\left(x^2 - xx_0\right) g \tag{3}$$

(having chosen to measure at y=0). Since x_0 is more generally a function of z as shown in Fig. 1, we express it as

$$x_0(z) = x_a - \frac{x_b - x_a}{L_m} a + \frac{x_b - x_a}{L_m} z \quad . \tag{4}$$

Then the flux of (2) becomes an integral over z given by

$$\Phi^{\pm} = \int_a^{a+L_m} A_z(\pm D,0) - A_z(0,0)\, dz \tag{5}$$

(assuming a motion step, D, is performed starting from x=0). The average offset position, δ_{co}, is determined from

$$\boldsymbol{d}_{co} = \frac{-D}{2} \frac{\left(\Phi^+ - \Phi^-\right)}{\left(\Phi^+ + \Phi^-\right)} \tag{6}$$

which using (3), (4) yields the average magnet center

$$\boldsymbol{d}_{co} = \frac{x_a + x_b}{2} \quad . \tag{7}$$

As a byproduct, the integral strength is $\int gdl = \Phi^+ + \Phi^-$. Details and analysis of errors are given in references [1]-[3].

2) AC Measurements: For small signal strengths (e.g. room temperature measurements of quadrupoles or measurements (warm or cold) of corrector elements), the DC technique may not afford sufficient accuracy. The MQX magnets have gradient ~18 T/m at 1 kA and would need 50-100 A for DC measurements to work well. Instead, an AC technique as used for Tesla focusing quadrupoles [3] must be employed. Here the wire is stationary, and the flux change is generated by magnet excitation with AC current. The Fourier component of measured flux matching the frequency of the AC power supply is determined at positive and negative wire positions. These fluxes are combined as for the DC measurements above. The AC set-up is shown schematically in Fig. 4.

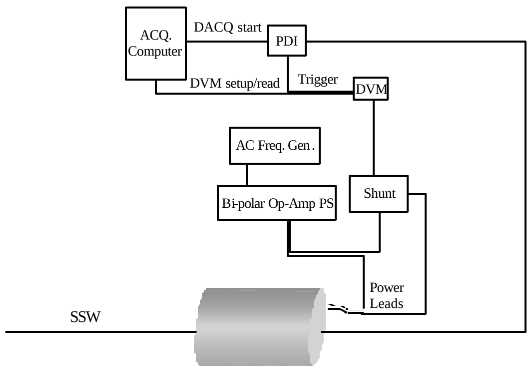

Fig.4. Schematic for SSW measurements with AC current.

The AC current is asynchronous to data acquisition; its frequency is chosen so that there are an integer number of cycles every 128 msec[1]. This gives a nominal frequency of 7.8125 Hz. By sampling the flux at 1kHz with the integrator, any 128 samples yields an integer number of AC cycles – there is no need to gate triggers. The current is simultaneously sampled with a DVM (triggered by integrator sampling) and is used to normalize the measured flux for power supply variations. An example of the signal to noise spectrum is shown in Fig. 5 for a 4-period measurement; noise rejection is more than four orders of magnitude.

3) Determining True Magnet Axis: Measurements are made with "co-directional" measurements as described by (5) as well as "counter-directional" measurements defined by

$$\Phi^{\pm}_{cn} = \int_{a}^{a+L_m} A_z\left(\pm D\left(1-\frac{2z}{L_w}\right),\, 0\right) - A_z(0,0)\,dz \qquad (8)$$

(one stage moving to $+D$, the other to $-D$). Using the $\Phi^{\pm}_{cn}$ in place of $\Phi^{\pm}$ in (6) yields the counter-directional offset

$$\delta_{cn} = x_a \frac{\alpha_1+\alpha_2}{\alpha_3} - x_b \frac{a_2}{a_3} \quad , \qquad (9)$$

where the alphas are geometric parameters defined by

$$\begin{aligned} \alpha_1 &= 1-\frac{b+a}{L} \\ \alpha_2 &= \frac{2a+4b-3L}{6L} \\ \alpha_3 &= 1-\frac{2(b+a)}{L}+\frac{4}{3}\frac{a^2+b^2+ab}{L^2} \end{aligned} \qquad (10)$$

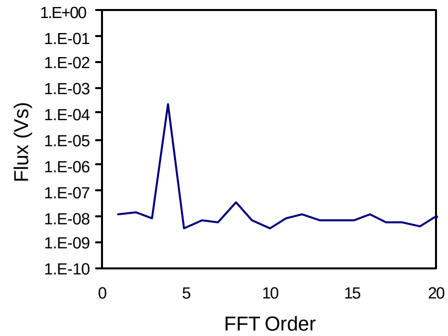

Fig.5. Fourier spectrum for 16 m SSW measurements with AC current.

and need to be measured at the level of a few cm. The δ_{co} and δ_{cn} expressions can then be solved to yield the wire positions at the ends of the magnet:

$$\begin{aligned} x_a &= \frac{1}{(\alpha_1+2\alpha_2)}\left(2\delta_{co}\alpha_2+\delta_{cn}\alpha_3\right) \\ x_b &= \frac{\left(2\delta_{co}\alpha_2-\delta_{cn}\alpha_3+2\delta_{co}\alpha_1\right)}{(\alpha_1+2\alpha_2)} \end{aligned} \quad . \qquad (11)$$

Accounting for the distances between magnet ends and stage positions, the stages can then be adjusted so that the wire is on the true axis of the magnet.

4) Sag Removal: Expressions thus far have been given without regards for wire sag (i.e. for the horizontal (x) axis). For the y-direction, the effects of wire sagitta must also be included. The y offset, y_0, as a function of the z of Fig.1 is

$$y_0(z) = y_a - \frac{y_b-y_a}{L_m}a + \frac{y_b-y_a}{L_m}z + \frac{1}{\kappa}\left\{\cosh\left[\kappa\left(z-\frac{L_w}{2}\right)\right]-\cosh\left(\kappa\frac{L_w}{2}\right)\right\} \quad , \qquad (12)$$

where $\kappa = w/T$ is the parameter of the catenary (w being the weight per unit length and T the tension). Sag effects can be eliminated by measuring y_0 as a function of $1/T$ and extrapolating to infinite tension [1], [2]. However, for long wire lengths, the extrapolation may be limited by errors in the tension measurement: frictional effects, gauge calibration, non-linearity, and torque effects, and changes in w (e.g. stretching). Careful calibration may be required to account for these errors and maintain the ~0.5% absolute tension accuracy required for a 20m wire. As an alternative, y_0 can be measured vs. $1/f^2$, where f is the fundamental frequency given by

$$f = \frac{1}{2L_w}\sqrt{T\frac{g}{w}} \quad , \qquad (13)$$

and κ is re-written as

$$\kappa = \frac{g}{4f^2L_w^2} \quad . \qquad (14)$$

f is excited by moving the stages at each end sharply downward. As the wire vibrates, flux is sampled at 1 kHz to determine frequency. δ_o and δ_n are measured at various $1/f^2$ and extrapolated to determine these quantities with no sag.

[1] It is convenient to choose a power of 2 so that an FFT can be used.

Sample data for a 16 m wire is shown in Fig. 6. The frequency measurement repeatability is ~0.3%.

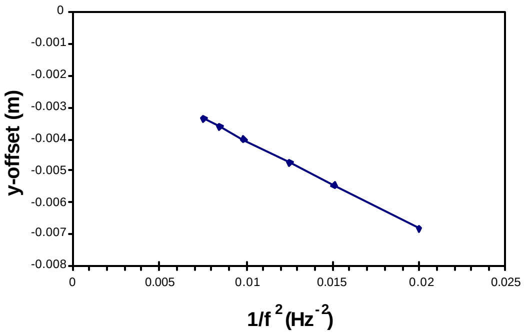

Fig.6. *y*-offset vs $1/f^2$ for 16m wire length (AC measurements with 10A).

5) Roll Angle: The roll and pitch angles of the stage units are first zeroed with respect to gravity using a µ-level (resolution 10 µrad) placed upon the stage unit base plates. Roll angle with respect to gravity is then determined by measuring δ_{co} for horizontal measurements, as a function of vertical position. The slope yields $-2\theta_{roll}$. Swapping stage units end-for-end allows calibration of the system offset caused by horizontal stage motions not being truly parallel to the base plates, non-orthogonality between horizontal and vertical stage axes, stage errors, etc. [2]. For the stage system presently in use, this offset is –50 µrad.

IV. Measurements With Different Wire Lengths

To demonstrate the practicability of the techniques of Section III, measurements were performed on a 2 m prototype magnet (HGQ05) at room temperature with wire lengths of 3.5, 11 and 16 m (limited by present cable lengths). These parameters represent a 'worst case' measurement from the viewpoint of signal size and magnet-length/wire-length ratio. AC measurements at 10 A were performed, with sag being removed using the $1/f^2$ method. Counter-directional measurements determined true magnet axis. Note that for the 16 m measurement, the wire was asymmetrically positioned with respect to magnet ends as will be the case during production measurements.

The goals were to confirm our ability to make low signal-strength measurements, and to verify consistency of alignment results over long wire lengths (i.e. our ability to remove sag effects). Since the actual position of the magnet axis is not known a priori, the 3.5 m measurement is treated as a baseline axis determination. Magnet average center and true axis are determined by SSW, and the fiducials on the stage are measured with the laser tracker. Subsequent magnet axis and stage fiducial measurements at 11 and 16 m are compared to the baseline to determine consistency with the original 3.5 m results. Deviations from these expectations are summarized in Table I. The average center measured for different wire lengths agrees to within 35 µm for both *x* (horizontal) and *y* (vertical). The repeatability for 11 and 16 m measurements in *y* was 15 and 25 µm respectively; for *x*, the repeatabilties were 3 and 6 µm. The error in measuring the true axis at the magnet ends is less than ~150 µm.

TABLE I
Errors In Axis Determination For 11 And 16 m Wire Lengths

	X-axis (m)		Y-axis (m)	
	11m	16m	11m	16m
Magnet End a	-0.000011	0.000100	0.000119	0.000092
Magnet End b	-0.000059	-0.000111	-0.000156	-0.000142
Center	-0.000033	0.000000	-0.000019	-0.000025

Note that for the true axis, the sensitivity is a function of L_m^2 and so this error should decrease significantly for longer length magnets. For extrapolation to infinite tension, the *1/T* method showed linearity as good as the $1/f^2$ method for the 11 m data. This was not true at 16 m (see Figure 7).

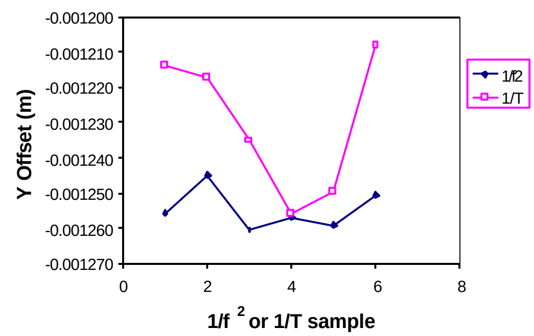

Fig.7. Non-linearity in *y*-offset vs $1/f^2$ and *1/T* measurements. Slope is removed from the data (e.g. see Fig. 6) and plotted vs sample number.

A single roll angle measurement was also performed with the 16 m wire. The uncertainty of the fitted slope was about 120 µrad.

V. Conclusions

An introduction to the SSW system and techniques for alignment of the MQX magnets for the LHC has been presented. Measurements aimed at demonstrating the ability of SSW to make accurate measurements of average axis, roll angle, and true axis with long wires and low signal strength have been performed. Results indicate that these issues will be manageable with respect to MQX alignment requirements.

Acknowledgment

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